An Analysis of the Historically Observed Period Change of UV Piscium, RT Andromedae, and XY Ursae Majoris Using a Markov Chain Monte Carlo Approach

Undergraduate Research Thesis

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Abstract

RT And, UV Psc, and XY UMa, all RS CVn type binaries, all have century long observational histories. All three stars have observed period change and the long span of data can shed light on the mechanisms responsible for this change. However, technological developments in observational methods have resulted in large heteroscedastic errors in the observational data. As a result, previous studies have largely ignored the photographic observations in the record. For the case of UV Psc, it is revealed, using a Markov Chain Monte Carlo Approach, that the photographic data narrows the possible period change model solutions. With the addition of the photographic data, angular momentum loss is concluded to not be the dominate mechanism of period change in UV Psc. A sinusoidal variation, whether due to a third body or the Applegate mechanism, is a more likely explanation.

1. Introduction

As the closest star to us, the Sun is pivotal in our understanding of stellar physics. Not only is it the longest studied star, it is also the only star close enough to spatially resolve. The Sun acts as a laboratory, a place where the behaviors and properties of stars can be closely observed and documented. However, our reliance on the Sun has caused some issues in stellar models. Because the Sun does not have a companion star, stellar evolution models assume single stars. This is an extreme approximation given that 44% of solar-type stars are multiplicities, i.e. 2 or more stars (Raghavan et al. 2010), and this fraction increases as the mass of the star increases. Therefore, binaries must be studied extensively to improve stellar models, and solar-mass binaries are an ideal target. Solar mass binaries are frequent and relatively bright, though the luminosity contrast between the stellar companions can be slight (Duchêne & Kraus 2013).

Binary stars must be observed continuously in order to provide insight on the processes through which the individual stars interact. Furthering our understanding of binary star interactions, especially with regard to magnetic activity, will aid in efforts to resolve existing issues in stellar evolution models, especially for low and intermediate mass binaries (Salaris & Cassisi 2017). Binary systems with shorter orbital periods are ideal for the study of binary star interactions as the components will orbit around each other fast enough that changes in their period can be observed on human timescales.

One group of ideal observational targets are RS Canum Venaticorum (RS CVn) type binaries. RS CVns have a solar type primary component, a mass ratio near one, and short periods (< 2 weeks) (Hall 1975). They are of particular interest when studying the mechanisms of period variations in binaries because their periods tend to change on the timescale of tens of years. RS CVn binaries differ from Algol type binaries because they are detached, which means neither star fills its Roche lobe. This negates the possibility of continuous mass transfer between the components, the likely cause of period change in Algol-type binaries. With the removal of continuous mass transfer, an in-depth study of the other processes of period change can be done. Further, RS CVn binaries have strong Calcium H and K emission lines outside the eclipse, a hallmark of magnetically active stars which implies that magnetic processes could be responsible for these stars' period variability.

This study looks at three RS CVn type binaries, RT Andromedae, UV Piscium, and XY Ursae Majoris, in order to determine if any period change has occurred and the mechanisms of that change. Details on the observational data set are described in section 2. A discussion of the methods of analysis is done in section 3.

1.1 The Binary Stars

1.1.1 RT And

The first light curve of RT Andromedae was recorded by Zinner (1916) in 1913. Despite this long observational history, the mechanisms of RT And's period change are still unknown. Located at right ascension 23:11:10.10 and declination +53:01:33.03, RT And is composed of a 1.1 $M_{\odot}$ primary component and a 0.8 $M_{\odot}$ secondary component which orbit each other with a period of 0.62893088 days (Manzoori 2009). Over the course of its more than 100 year observation history, RT And's period has been observed to have decreased. The mechanism of this observed decrease is highly contested. The issue stems from the fact that, as recently as 2009, it was impossible to tell if the residual O-C from a linear ephemeris was parabolic or sinusoidal. The presence of a long period low mass third body (Erdem et al. 2001), instantaneous mass transfers from the primary to the secondary component (Pribulla et al. 2000), or magnetic braking due to the Applegate mechanisms (Manzoori 2009) are therefore all credible theories given the current observational data. New observations might be enough to shed light on this problem and if not, it is crucial to model and assess how far into the future observations will need to continue in order to determine the mechanisms of period change in RT And.

1.1.2 UV Psc

UV Piscium is a model RS CVn type binary and with recorded eclipses dating back to 1899, it is the system with the longest observation history in this study. UV Psc is located at right ascension 01:16:55.1 and declination + 06:48:42.1 and made up of a 1.0 $M_{\odot}$ primary component and a 0.9 $M_{\odot}$ secondary component which orbit each other with a period of 0.8610515 days (Jeong et al. 2019). A study with a complete compilation of the historical minima was published just last year (Jeong et al. 2019), so for the case of UV Psc this study will add new observations and focus on a more in-depth statistical analysis of the historical data. If there is any period change in UV Psc it is small, making it extremely important to carefully deal with the heteroscedastic errors inherent in older data. Sowell (2001) found no period change with an improved ephemeris, however others have found both a decreasing (Sadik 1979) and an increasing (Hall & Kreiner 1980 and Milano et al. 1986) orbital period. Any observed period change has been explained by any number of processes: the existence of a third body (Jeong et al. 2019, Shengbang et al. 1999), mass transfer (Sadik et al. 1979), and the magnetic activity cycle of the primary component (Shengbang et al. 1999). To an even greater extent than RT And, it is unclear if UV Psc's O-C residual is parabolic or sinusoidal thus special attention must be paid to predicting how long into the future observations must extend to conclude the mechanism of period change.

1.1.3 XY UMa

XY Ursae Majoris is considered to be the most magnetically active of the known RS CVn binaries. Located at right ascension 09:09:55.94 and declination +54:29:17.73, XY UMa is made up of a 1.1 $M_{\odot}$ primary component and a 0.6 $M_{\odot}$ secondary component which orbit around each other with a period of 0.47899678 days as computed by Yuan (2010). The first photometric observation reported in Geyer & Metz (1977) dates to 1931, thus a long observational and scientific record of XY UMa's activity exists. Such a long observation history means an in-depth study of XY UMa's period change is possible. When fit with a linear ephemeris, XY UMa has been observed to have a sinusoidal O-C residual with a period of 25-40 years (Pojmański and Geyer 1990, Erdem and Güdür 1998, Chochol et al. 1998, and Yuan 2010). Sinusoidal O-C residuals are an indicator of a third body in the system and as such XY UMa's period change has been explained as a third body (Chochol et al. 1998, Pojmański and Geyer 1990, and Pribulla et al. 2000). However, in more recent studies, evidence has emerged for a quadratic term in the O-C residual that previous explanations of a third body do not adequately explain (Yuan 2010). This muddles the picture of the mechanics in the system and it has been suggested that XY UMa's period change is due to a combination of the Applegate mechanism and mass loss due to stellar winds (Erdem and Güdür 1998). The continuing discussion around the observed period change makes XY UMa a compelling target for additional observations and statistical analysis.

1.2 The Mechanisms of Period Change

The three stars this study focuses on, RT And, UV Psc, and XY UMa, have at least one of three mechanisms responsible for the period change observed in these systems, third body motion, the Applegate mechanism, or mass loss due to stellar winds. Many of these mechanisms exhibit the same or similar features in the O-C residual when fit with a linear ephemeris, the only way to distinguish one from another is a large number of observations of the system over long timescales (Pribulla et al. 2005).

1.2.1 Third body Motion

Only 11% of solar type stars are known to be in systems with more than 2 stars (Raghavan et al. 2010). However, these are only the known systems, it is entirely possible that more triple systems exist with dim third bodies not easily visible from Earth. Current stellar evolution models show that wide, multiple star systems are a common result of cloud collapse forming stars (Duchêne & Kraus 2013). Thus, multiple star systems may be more common than seen in observations. Further, binary systems can also be influenced by large planets which are massive enough to have an observable effect on the system's barycenter. A binary with a third body will orbit around the whole system's center of gravity. When the binary is farther away from Earth, its eclipse is observed to be later than expected and earlier when closer due to light travel times. This phenomenon in eclipsing binaries is known as LITE, or the light-time effect. As such, one of the popular explanations for period change in binary systems is the existence of a third body. Other than LITE, there are two other photometric features which can be observed as evidence for a third body: a third light source in the light curve and the orbital inclination changing due to third body tidal interaction (Pribulla et al. 2005). Of these observables the simplest to observe, for the three systems in this study, is LITE, resulting in a sinusoidal O-C residual when eclipse timings are fit with a linear ephemeris. This sinusoid will exhibit a regular period which will be the characteristic period of the third body.

1.2.2 The Applegate Mechanism

The orbit of a binary star system is gravitationally coupled to the physical shape of the magnetically active star. As a star goes through its magnetic activity cycle, the star is deformed by redistribution of angular momentum on its surface (Applegate 1992). This process is known as the Applegate mechanism. These fluctuations result in small orbital variations that can result in long term cycles in the binary period. Period variation as a result of the Applegate mechanism is on timescales of decades or longer, like that seen in all three systems in this study. Other photometric evidence for the Applegate mechanism can be seen in: long term changes of the average brightness that vary with the observed changes in the orbital period. The magnetically active star getting bluer as it brightens, and changes in luminosity on the order of 0.1 magnitude. Unlike third body motion the Applegate mechanism can result in non-periodic period change, all that is required is a strong enough magnetic dynamo action in the magnetically active star to generate torque and redistribute the stars angular momentum. The smaller the separation between the two stars, the smaller shape change is needed to affect the period (Völschow et al. 2016), so short period binaries are ideal candidates for observing the effects of this mechanism. RS CVns are magnetically active and exhibit possible surface spots, a good indicator of strong dynamo activity (Schleicher & Mennickent 2017). However, there has been considerable debate over whether RS CVn type binaries have strong enough dynamo action to cause the observed period variation as a result of the Applegate mechanism alone. Völschow et al. (2016) looked at a sample of 12 binaries, including some RS CVn binaries, and found that the energy required to cause the period change observed was greater than the magnetic field provided by the star. However, many observers (Manzoori 2009, Shengbang et al. 2004, Erdem and Güdür 1998) have found that the characteristics expected for a system with period change due to the Applegate mechanism are observed within RS CVn binaries.

1.2.3 Mass Loss and Angular Momentum Loss

All the stars in this study are detached, which means that neither star fills its Roche lobe, thus mass transfer due to Roche lobe overflow is very unlikely. However, mass transfer can still occur in detached systems when stellar wind mass loss results in a mass ejection in the direction of the first Lagrangian point, where the two Roche lobes touch, of the system. When outflowing stellar winds are forced by the stars magnetic fields to corotate with the star at the Alfvén radius, the point at which the magnetic field dominates the flow of particles, the orbital period of the binary system will decrease because angular momentum has been removed from the system (Erdem et al. 2001). This process is known as angular momentum loss or magnetic braking. This is a good explanation for the period decrease observed in this study's systems since the binary components are close enough to have spin-orbit coupling due to tidal effects, a requirement for angular momentum loss. The binary system's period decrease is therefore due to both the stellar wind driven mass loss and the angular momentum loss due to spin-orbit coupling (Demircan 2006).The process of angular momentum loss will eventually result in a contact binary, how fast it reaches this state depends on initial separation, stellar magnetic activity, the strength of the stellar wind, and the braking mechanism (Demircan 1999). The period decrease due to stellar wind mass loss and angular momentum loss is relatively constant, as such O-C residuals will not showcase a sinusoid as is the case with third body motion and the Applegate mechanism, but rather a downward facing parabola whose quadratic term denotes the period decrease.

2. Data Collection

This study relies on an extensive collection of eclipse timings found in the literature over the last century and modern observations taken within the last two years. In this section, the process through which that collection was acquired is detailed.

2.1. Historical Data Collection

UV Psc, XY Uma, and RT And were all selected for their long historical record. In some cases, this record goes back 100 years. In order to fully make use of the observational histories of these binaries, papers with published eclipse timings were collected through the use of the SAO/NASA Astrophysics Data System, or ADS. Many of these papers were collections of eclipse timings from previously published papers, similar to what is done in this study. For these collections, the referenced papers were tracked down where possible and the reported timings were verified. Further, any errors in the eclipse timings reported by the observer where recorded. A few collections of observations done by the same observers over a long period were used to determine if published errors were to be trusted. This was done in the usual manner through a least squares fit. The number, type of eclipses, range of dates, and literature sources of the timings found for each target is illustrated in Table 1.

Eclipse numbers were assigned using the most recent linear ephemeris. The zero-point observation was subtracted from the Heliocentric Julian Date (HJD) of all the observations and that number was then divided by the reported orbital period. For RT And, the linear ephemeris reported in Manzoori (2009) was used,

Star	Literature data was taken from	Year of first observed eclipse	Number of primary eclipses from historical record	Number of secondary eclipses from historical record	Number of primary eclipses from current paper	Number of secondary eclipses from current paper
RT And	Manzoori (2009), Pribulla et al. (2000), Williamon (1974)	1913	512	29	3	4
UV Psc	Jeong et al. (2019)	1899	235	31	Our data	Our data
XY UMa	Yuan (2010), Pojmański & Geyer (1990), Chochol et al. (1998), Sowell et al. (2001), Erdem & Gügür (1998)	1931	211	20	4	2

Table 1. Number of minima times collected from historical sources and added by this work. Both RT And and UV Psc have eclipse timings from over 100 years ago, and XY UMa is not far behind. These stars' long historical records are integral to determining the methods of period change observed in these stars. The second column of this table denotes the paper which these eclipse timings were pulled from. Jeong et al. (2019) was used as the only source for UV Psc since it was determined that it contained a complete historical record.

$$T_{minI} = 2436697.857 + 0.62893088E, \tag{1}$$

where T_{minI} denotes the time at which the primary minimum will occur, and E denotes the epoch of the observation. For UV Psc, the linear ephemeris used was applied by Jeong et al. (2019) but was originally reported in Kreiner (2004),

$$T_{minI} = 2452500.0411 + 0.8610468E. \tag{2}$$

For XY UMa, the ephemeris quoted in Yuan (2010) was used,

$$T_{minI} = 2454830.40260 + 0.47899678E, \tag{3}$$

where T_{minI} and E are defined similarly for both the UV Psc and XY UMa ephemerides.

2.2 Observational Data Collection

XY UMa was observed in the spring of 2019, RT And in the autumn of 2019, and UV Psc was observed in the autumn of 2018. Because these stars are bright, all observations were done using a narrow band filter centered on H-alpha (656.3 nm) on the 1.3 and at 5007 Angstroms on the 2.4 m MDM telescopes. Both telescopes are located on Kitt Peak in Arizona. Basic processing of the raw data frames included overscan correction, interpolation over bad columns, and flattening using twilight sky exposures. All observations had generally non-photometric conditions. Differential aperture photometry was obtained

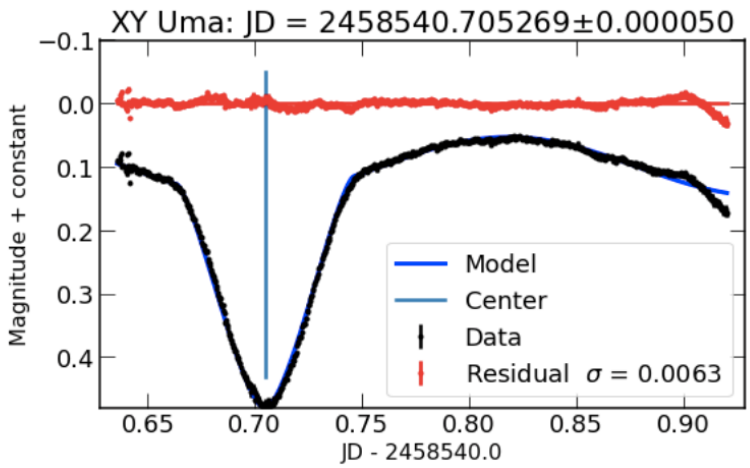


Figure 1. UT 2019 February 26 light curve from primary eclipse of XY UMa taken with 1.3 m telescope at MDM. This light curve, black, contains 867 points taken with an exposure time of 20 seconds over a span of 6.84 hours. An MCMC approach was used to establish the values of each model parameter as determined by the mean of the posterior distributions. The residuals of the model are shown in red, where σ is the standard deviation as determined by MCMC.

with respect to other stars in the field. For the most part, these reference stars were considerably fainter than the binary, so errors in the differential photometry are dominated by errors in the photometry of the comparison stars.

A light curve for XY UMa taken on UT 2019 February 26 is shown in Figure 1. This observed primary eclipse was recorded with the 1.3 m telescope and contains 867 points over a span of 6.84 hours with exposure times of 20 seconds. Similar exposure times were used for all three stars, resulting in light curves of similar quality.

The light curve pictured in Figure 1, and all other light curves collected during the duration of this work, was fit with a sinusoidal background with the parameters: amplitude, period, and phase. The sinusoidal background is used to remove star spots, which all three stars have been observed to possess, from the light curves. The eclipse was modeled using the power law functions, known as the New Algol Variable (NAV) method, described in Andropov (2012). The parameters of the eclipse included in the fit were duration of the eclipse, center time, and shape. NAV method for modeling light curves generally fits the in-eclipse light curves reported in this study very well despite the fact that it does not take into account physical models of other stellar phenomenon which would impact light curves, like stellar radii, temperatures, and limb darkening. The parameters used to fit the modeled light curves were the central values, i.e. the mean, of the posterior distributions obtained using a Markov Chain Monte Carlo (MCMC) (See section 3.1 for more information). It is assumed that the errors in the model are random, and independent and identically distributed as a normal characterized by a mean of 0 and variance σ^2. The minima timings were therefore determined to be the center of the modeled light curve. These timings were then assigned epoch numbers following the method used for the historical data described in section 2.1.

3. Data Analysis

Due to the significant technological changes which have occurred in astronomy over the timescale of the data, these tabulated eclipse timings exhibit heteroscedastic error which must be carefully dealt with. The oldest data was recorded with photographic plates and have errors on the order of tens of minutes for these stars, while the data collected at Kitt Peak in the last two years has error on the order of tens of seconds.

3.1 A Markov Chain Monte Carlo Approach

Markov Chain Monte Carlo (MCMC) is a method of obtaining the posterior distributions for parameters of interest using Bayesian statistics. To find the posterior distribution, a MCMC algorithm produces Monte Carlo simulations that rely on the properties of Markov chains and then accepts them at a rate known as the acceptance rate (Kathan 2019). Monte Carlo simulations determine parameters by generating random numbers according to a proposal distribution. Markov chains are sequences of events which are related to each other probabilistically, they do not use require information outside of the current state and are therefore useful in determining the long-run tendencies of a variable (Shaver 2017). In the simplest way possible, MCMC generates random values and determines whether that value is likely to be a sample of the posterior based on the data and prior beliefs.

This work uses a MCMC approach to ascertaining parameters rather than the traditional least-squares fit, because MCMC offers more flexibility. A MCMC approach takes prior knowledge into account and uses

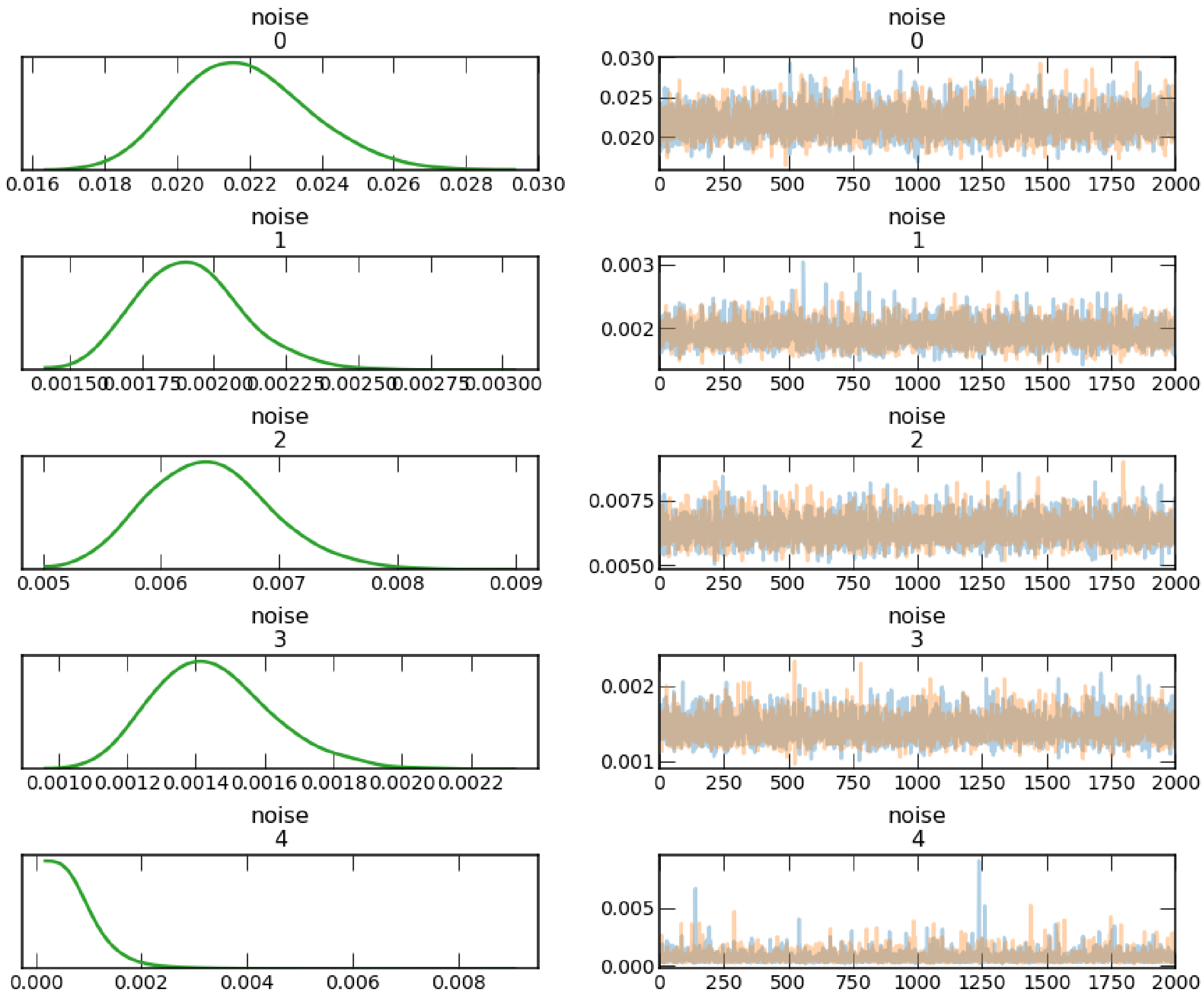


Figure 2. Error assignment for data grouped by observation methods for UV Psc data. Pictured on the left: posterior distributions of error values, called noise here, for each class of observations, when fit to a quadratic model denoting steady period change. Units are in days. Noises are numbered such that 0 is photographic observations, 1 is photoelectric, 2 is visual, 3 is CCD, and 4 is observations done as part of this work. Pictured on the right: trace of MCMC used as check of convergence. Note that there is no trend in any of the traces showing that the fit converged.

that knowledge to determine the posterior, and therefore the uncertainty in a parameter as well (Orloff & Bloom 2018). In the case of this data, the zero-point and orbital period of each binary system is well known and should factor into the models of orbital change. Further a MCMC approach does not assume the same experimental methods across all the data as the traditional least squares fit does and is therefore the better statistical approach for data of varying quality and experimental method.

3.2 Dealing with Heteroscedastic Error using MCMC Methods

Because the eclipse timings in this study came from varied sources different levels of technology, error assignment is difficult. MCMC determines the errors in each observational type while fitting, this is important because period change is extremely time dependent and the error in these observations is heteroscedastic in time and can therefore significantly affect the model results. MCMC allows for the determination of the model's dependence on the error and as such MCMC was used for this analysis. First the data for each star was fit to a linear ephemeris, where the zero-point observation is the intercept and the orbital period is the slope, using an unweighted least-squares fit. The zero-point and orbital period determined by the least-squares fit were then used as priors and fit to a normal distribution, with a variance of σ^2, using an MCMC approach to determine the error in these values. From there the data was grouped by observational method, i.e. photographic, photoelectric, CCD, etc. Each observational method was assumed to have similar errors and as such was fit to a normal distribution again using an MCMC approach to determine the magnitude of the errors for each group. Unsurprisingly, photographic observations had the greatest error, while CCD observations had the least error when only considering the historical data. This phenomenon can be seen in Figure 2 which shows error assignment by observational method for UV Psc's observational data when fit by a steady period change model as determined by the posterior distribution determined by MCMC. In figure 2, the term noise is used to denote the error in each group; noise 0 denotes photographic observations, 1 is photoelectric, 2 is visual, 3 is CCD, and 4 is this work's observations and as expected the error in the CCD and this work's observations are the smallest.

4. Results

A binary system whose orbital period is not changing will be fit to a linear ephemeris and showcase no evidence for a quadratic term in the O-C diagram. In the simplest case of period change, steady increase or decrease, the O-C diagram, for a fit to a linear ephemeris, will exhibit a parabolic shape. For steady period change the ephemeris contains a quadratic term and will be in the form,

$$T_{min,I} = t_0 + P_0 E + \frac{1}{2} P_0 \frac{dP}{dt} E^2, \tag{4}$$

where t_0 is the zeroth eclipse, P_0 is the orbital period, dP/dt is the observed period change, and E is the eclipse number. In the literature, $\frac{1}{2} P_0 dP/dt$ is denoted as Q and is often the citied value indicating the extent of period change. Mass loss due to stellar winds will be a constant period change and can therefore be modeled by Eq (4). Period change due to a strong magnetic dynamo action will include a cosine or sine term as well (Applegate 1992, Erdem & Güdür 1998). For change due to a third body, a complex function of sines and cosines must be added, this function depends on numerous orbital parameters and the systems center of gravity (Pribulla et al. 2005).

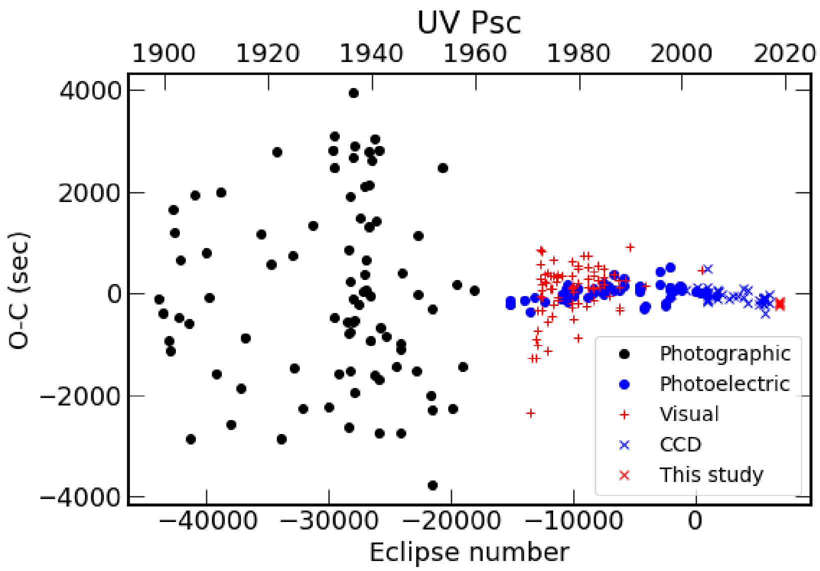


Figure 3. O-C for UV Psc when fit with a linear ephemeris using an unweighted linear LSQ fit. The O-C from non-photographic data, shows a slight trend which suggests the need for a quadratic term in the ephemeris. This fit gives a rough estimate of the error for each observational group, shown in legend. The photographic data is good to about 30 minutes, the visual data to about 9 min, the photoelectric data to about 2 min, and the new observations to about 20 seconds.

4.1 UV Psc

Due to the recent Jeong et al. (2019) paper on UV Psc, UV Psc was selected as the first focus of this work to determine how much a detailed consideration of the heteroscedastic error would improve the determination of period change.

To begin with UV Psc was fit to a linear ephemeris using an unweighted linear least square (LSQ) fit, as seen in Figure 3. The non-photographic data (post-1960) exhibits a slight trend which indicates the need for at least a quadratic ephemeris. The photographic is too varied to visually add to this trend. This study's observations fit into the observed trend well which indicated that the timing methods used are consistent throughout the sample. The data grouped by observational method in order to assign error as discussed in section 3.2. The linear LSQ fit was not used to assign errors to the data based on the different observational methods but it can be used for a rough idea of the amount of error in each group. This fit shows that the photographic data is good to about 30 minutes, the visual data to about 9 minutes, the photoelectric data to about 2 minutes, and the new observations to about 20 seconds. A more precise linear fit with source errors is done using an MCMC approach. This linear fit is used as the baseline model for the rest of fits and O-C plots included in this paper. It exhibits the same features as the simpler unweighted linear LSQ fit.

Given the observed trends in the O-C of UV Psc when fit to a linear ephemeris, the data was fit to an ephemeris for steady period change, Eq (4). The parameters, t_0, P_0, and Q, were determined using an MCMC approach, the results of which are shown in Figure 4 along with the respective traces. The average Q for this model of UV Psc was found to be -1.17×10^{-11} per orbit, which gives an average period change of -3.15×10^{-16} per second.

The steady period change model using the estimated parameters and the errors for the different observational methods, shown in Figure 2, was plotted against the original O-C determined from the linear ephemeris fit, the result is illustrated in Figure 5. The model, shown in black, was fit to all points.

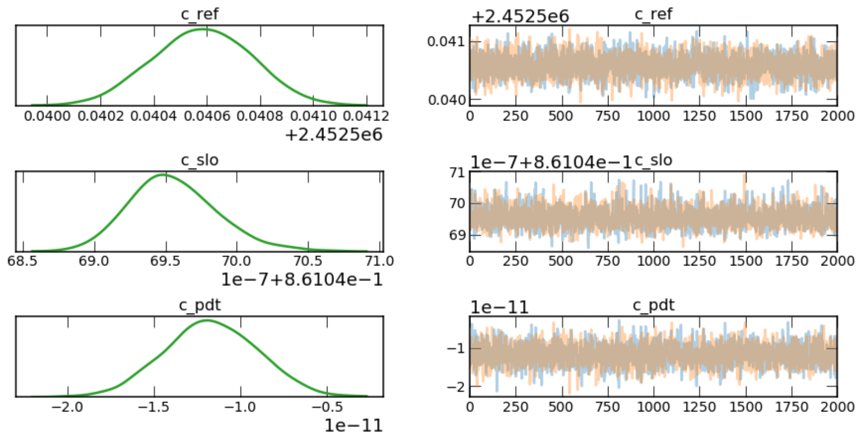


Figure 4. Posterior distributions of parameters of quadratic ephemersis as determined by MCMC approach. Using the notation in Eq (4), c_ref is the paracter t_0, c_slo is the parameter P_0, and c_pdt is the parameter Q. dP/dt, the average period change per second, was found to be -3.15×10^{-16}.

The cyan lines surrounding the model indicates the range of solutions which make up the probability density functions. As expected, the envelope is notably smaller for the modern data as that data has smaller errors.

While the introduction of a quadratic term improves UV Psc'c ephemeris, this model is not the best fit of the data. This model does not quite go through the median of the photographic points, as it would if it is assumed that all the photographic points have equal weight. More importantly, the most recent solutions do not fit the curvature of the modern data well. The model is a little higher than the most recent data indicates it should be.

One of the main objectives of this work is to assess the utility of a more statistically rigorous approach to determining period change in stars whose observational histories contain heteroscedastic errors. In Jeong et al. (2019), the overshoot of recent observations by the constant period change model was dealt with by reducing the weighting on the photographic data, as they do not obviously follow the trend of the modern observations. To determine if the photographic data did in fact add nearly negligible information, as assumed by Jeong et al., the photographic data was removed from the model fit. A comparison of the fit with and without the photographic data is shown in Figure 6.

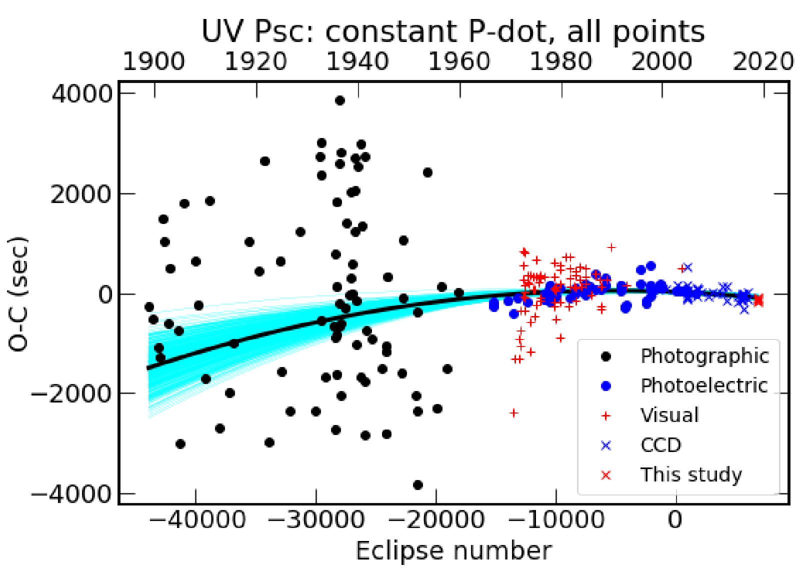
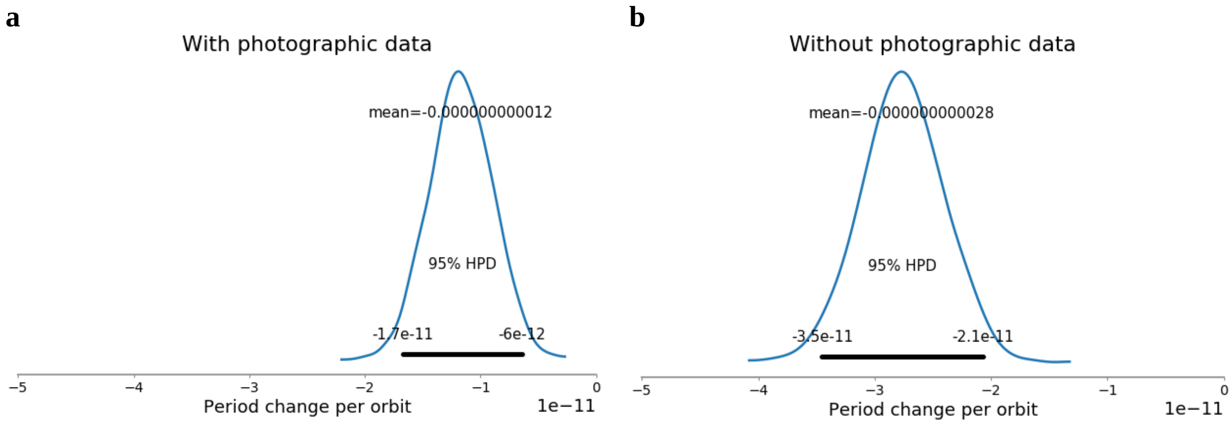


Figure 5. Linear O-C of UV Psc fit, using an MCMC approach, to a quadratic term indicating steady period change. The model, shown in black, was fit to all points. The cyan envelope indicates the range of solutions in the probability density functions. This model overshoots the most recent data while not describing the curvature in the modern data well. It also does not pass through the median of the photographic data.



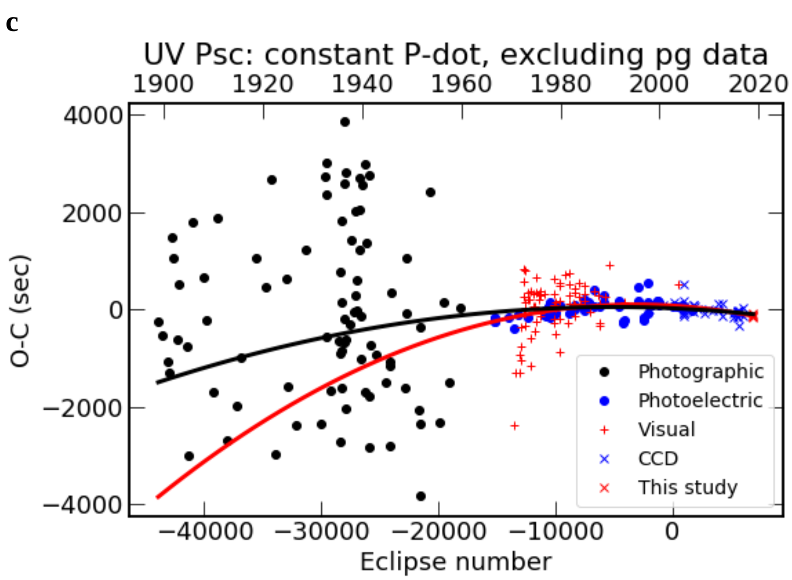


Figure 6. Comparison of fit to steady period change model with and without photographic data included. Depicted in c, the black line indicates the model when the photographic data is included, and the red line indicates the model when the photographic data is not included. When the photographic data is excluded the model fits the modern data better and predicts a much higher average period change, -2.77×10^{-11} days per orbit. However, the posterior distribution of the period change parameter is much narrower when the photographic data is included, see a, than it is when it is excluded, see b.

However, the posterior distribution of the period change is much narrower when the photographic data is included. The width of the period change, Q, posterior, as defined by containing 95% of the distribution, was -1.38×10^{-11} for the fit without the photographic observations compared with -1.04×10^{-11} when included. This indicates that the photographic data adds valuable information to the model. Therefore, we conclude that a steady period decrease does not adequately explain the observed O-C for UV Psc.

Given the lack of agreement between the baseline O-C and steady period change models, the obvious next step is to see if it is better described by a sinusoidal term. For simplicity, at this time, this fit is done with only sinusoidal term and no quadratic term, one will be added as this work progresses. This model therefore describes a system with no long-term period change. The periodic modulation model is shown in Figure 7, the black line indicates the model and the cyan lines surrounding the model indicate the range of solutions which make up the probability density functions. Therefore, the cyan lines create an increasingly fat envelope as the data gets older. As the fit of constant period change showed that the photographic data improved the certainty of the parameters, all observations were once again included in

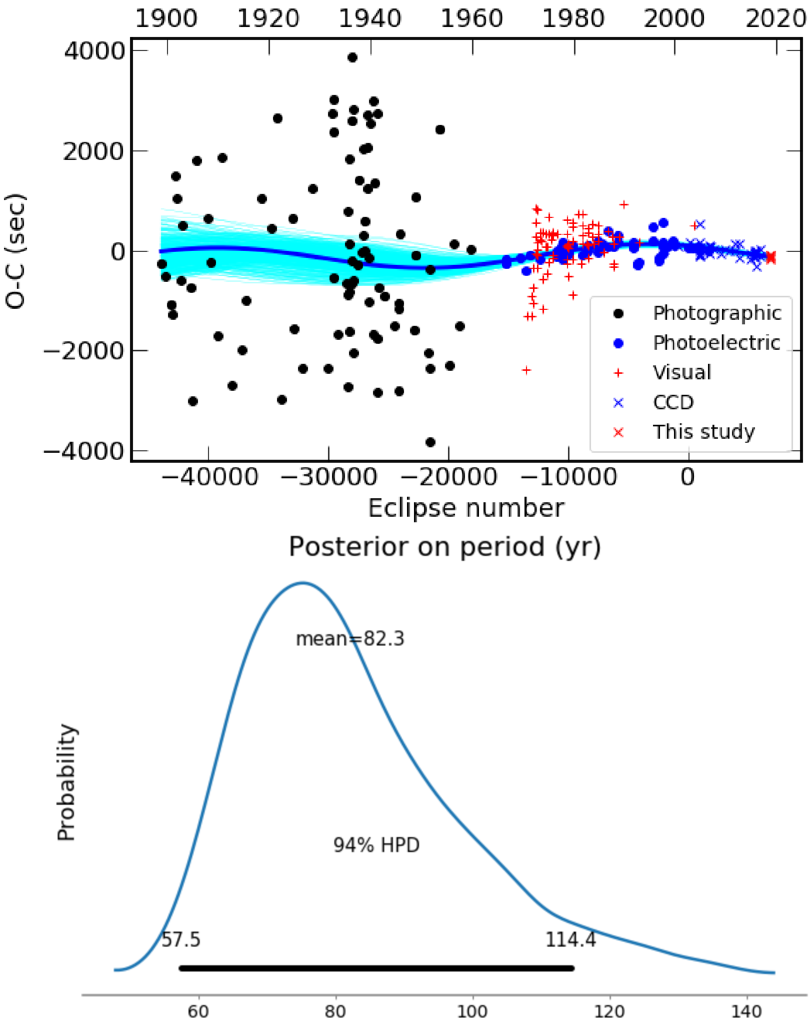


Figure 7. O-C of UV Psc fit, using an MCMC approach, to an ephemeris indicating sinusoidal period change. Top: the black line indicates the model, which was fit with all the observations, and the cyan lines surrounding the model indicate the range of solutions which make up the probability density functions. This periodic modulation model fits the newest data better than the constant period decrease model, it also passes through the photographic data near the median. Bottom: The posterior on the period shows that the predicted average period of variation is 82.3 years. 94% of the posterior distribution falls within a span of 56.9 years.

this fit. This fit does a much better job of predicting the newest data and it also passes through the photographic data near the median value.

The periodic modulation model predicts a period of 82.3 years. The posterior on the period, also depicted in Figure 7, contains 94% of its distribution within a width of 56.9 years. No other published work has fit UV Psc, with a comparably sized observational record, to a model which includes a periodic modulation without a quadratic term. Jeong et al. and fit the O-C of UV Psc to a sinusoid, however they also included a quadratic term and weighted the photographic data as nearly negligible. Despite this, they found a period of 73(±42) years which agrees with the period calculated in this work.

The amplitude of the periodic variation in the O-C was estimated to be 2.47×10^{-3} days, or 213 seconds. This value is also comparable to the value determined in Jeong et al. which was $2.3(\pm1.7)\times10^{-3}$ days. This value can be used to determine the potential mass of the third body as well as the strength of the magnetic field necessary to cause this attitude of change due to the Applegate mechanism, and these subsequent values can be used to infer which is the most probable effect.

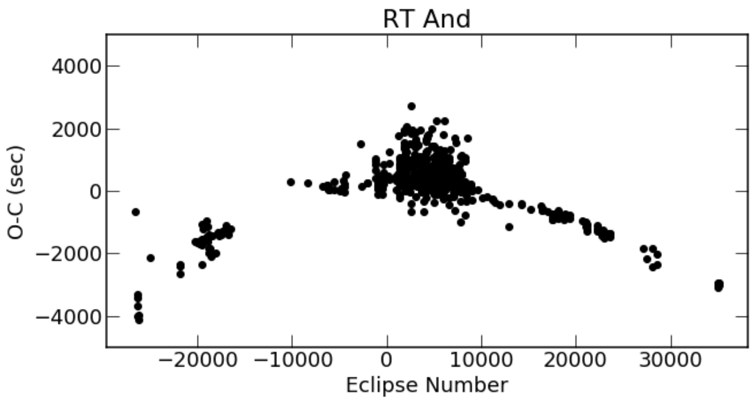


Figure 8. O-C for RT And when fit with a linear ephemeris using an unweighted linear LSQ fit. The O-C for RT And exhibits a mostly smooth parabola shape which could be an indicator of constant mass loss due to stellar winds as described by Eq (4). The clump of data points at the top of this O-C are from visual AAVSO observations. Further work will assess how much information these visual observations add to the predicted models of period change.

4.2 RT And

The O-C of the periods of RT And when fit with a linear ephemeris as determined by an unweighted linear least square (LSQ) fit, can be seen in Figure 8. RT And exhibits a clear parabolic shape, though this may be top of a sinusoid. New observations reported in this work extends the observational data by a decade, these observations are located on the far right of the O-C. The scatter at the top of this feature is due to visual observations from AAVSO (American Association of Variable Star Observers), further analysis is needed to determine if these observations add valuable information to any models of the period change on RT And.

Given the parabolic shape of the O-C, the first model that was fit to RT And's period change was a steady period change model as described by Eq (4). The results of this fit, when the photographic observations are included, are shown in Figure 9 as the black line. This model is problematic as it does not predict this works observations, which are the most accurate observations in the record. A solution excluding the photographic observations, shown in red, was also attempted in an effort to resolve this issue. While the model which excludes the photographic data fits the most recent observations better than the model which excludes the photographic data it still does not predict the MDM observations satisfactorily. It can be

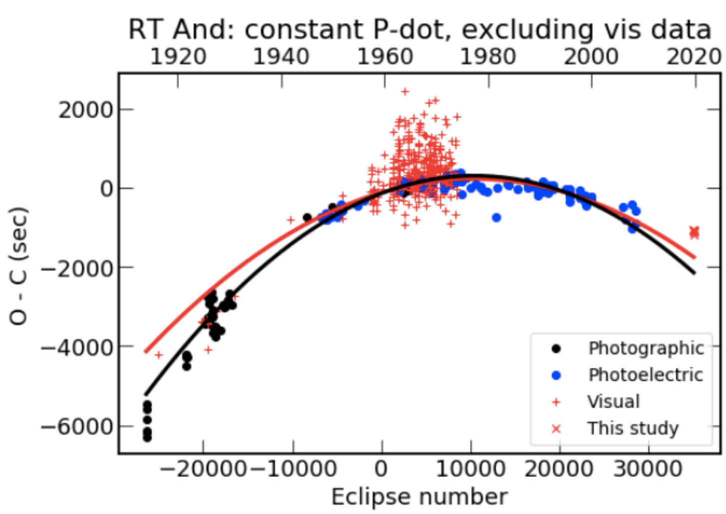
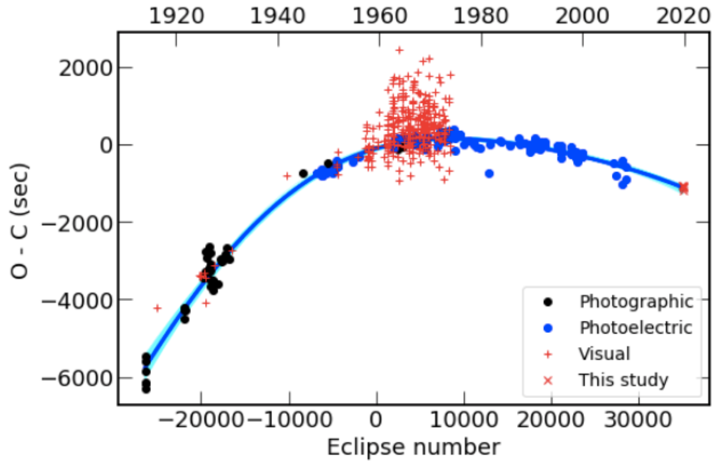


Figure 9. Linear O-C of RT And fit, using an MCMC approach, to a quadratic term indicating steady period change. The black line is the steady change model when fit to all the data. The red line is a steady change model with the photographic data excluded. Both the red and black lines significantly overshoot the most recent observations, denoted by red x. This indicates that despite the perceived shape of the O-C, the method of period change in this system in not mass and angular momentum loss.

Figure 10. O-C of RT And fit, using an MCMC approach, to an ephemeris indicating sinusoidal period change. The blue line denotes a model which includes both a quadratic and a sinusoidal term. The cyan envelope surrounding the model indicates the possible models as determined by MCMC. This model fits both the oldest and newest data very well, indicating that RT And's period change is either due to a third body or the Applegate mechanism.



safely stated that the mechanism of period of change for this system is not mass and angular momentum loss.

Given that RT And does not fit a simple quadratic model well, a sinusoidal term was added to the quadratic model to determine if RT And's period behavior could be better described by a third body of the Applegate mechanism. This model, shown in blue in Figure 10, fits the photographic data well and predicts the most recent observations perfectly. This indicates that the period change seen in RT And is either due to a third body or the Applegate mechanism.

4.3 XY UMa

Unlike RT And and UV Psc, XY UMa has yet to be thoroughly analyzed and work on this system is ongoing. The O-C when fit to a linear ephemeris, see Figure 11, does not seem to exhibit any clear behavior that can be well defined with a simple quadratic or sinusoidal term and the observations added by this work, located on the far right edge, do not seem to fit into what little pattern does exist. The majority of the current published research on XY UMa considers only the data in the center of the O-C which showcases a recognizable sinusoidal pattern, the addition of the new observations done at MDM indicates that this simple model is incorrect.

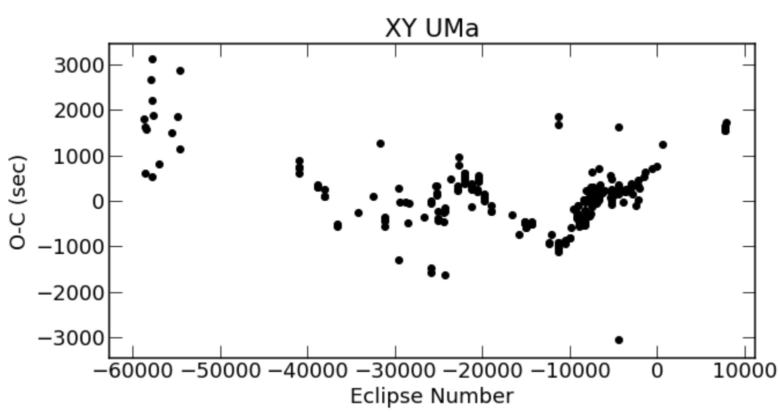


Figure 11. O-C for RT And when fit with a linear ephemeris using an unweighted linear LSQ fit. This data is quite messy with few stray points which should be triple checked or thrown out. Moreover, the observations taken as part of this work, located in the upper right, do not follow the sinusoidal pattern inferred by eclipses -30000 through -5000 which indicates complexity in the systems period, and likely more than on mechanism of orbital change.

5. Conclusion

While this work is ongoing, preliminary results from the analysis of observed eclipse timings for UV Piscium over the past century suggest that the system's orbital period exhibits some form of sinusoidal variation rather than steady period change. This indicates that the dominate mechanism for period change in this system is not mass, or angular momentum, loss due to stellar winds. Further work will determine if the observed periodicity in UV Psc'c linear O-C is due to a third body or the Applegate mechanism. The major conclusion of this work at this stage is that using an MCMC approach shows that the earliest data adds valuable information which narrows the span of the model's probability density functions, at least for UV Psc. This conclusion is significant, all pervious works on UV Psc, and many other RS CVn type binaries, have excluded the photographic data, or weighted it nearly negligible, when drawing conclusions about period change. In the case of UV Psc, the addition of the photographic data helped to narrow down the possible period change mechanisms and it is reasonable to believe this will be the case for many other RS CVn binaries as well. An MCMC approach, both with regards to heteroscedastic error assignment and estimating model parameters, on similarly long spanning observational records can therefore by reliably argued for by the results of this work.

With regards to RT And and XY UMa, the new observations have extended the observational record enough to show that previously held theories about the mechanisms of period change occurring in these binaries are incorrect. In the case of RT And, new observations show that the observed period variation in the O-C is sinusoidal in nature rather than parabolic. Similarly, a preliminary look at the linear O-C diagrams of XY UMa indicates that a simple sinusoidal model of the linear O-C is not sufficient to describe the observed period change.

6. Future work

The linear O-C of UV Psc remains to be fit to a model which includes both a quadratic term and a sinusoidal term. The two models which will be fit at as part of this work are a third body and the Applegate mechanism with long term period change. The ephemeris of an eclipsing binary experiencing long term period change due to a third body is,

$$T_{min,I} = t_0 + P_0E + \frac{1}{2}P_0\frac{dP}{dt}E^2 + \frac{a_{12}\sin i}{c}[\frac{1-e^2}{1+e\cos v}\sin(v+\omega) + e\sin\omega], \tag{5}$$

as defined Irwin (1959), where *e* is the eccentricity of the third body orbit, *v* is the true anomaly of the binary on its orbit around the three body systems center of gravity, ω is the longitude of the periastron passage of the three-body systems orbit, and *c* is the speed of light, all other variables are defined in Eq (6). Likewise, the ephemeris for an eclipsing binary experiencing long term period change due to the Applegate mechanism is modeled by,

$$T_{min,I} = t_0 + P_0E + \frac{1}{2}P_0\frac{dP}{dt}E^2 + \frac{AP_0}{2\pi v}\cos(P_0vE), \tag{6}$$

where *v* is period of the observed orbital variation and *A* is the amplitude, all other variables are defined in Eq (4) (Applegate 1992). The first sanity check for these fits is the mass of the third body, as determined by the amplitude of the observed periodic variation and the equation

$$f(m_3) = \frac{(a_{12}\sin i)^3}{P_2^2} = \frac{(m_3\sin i)^3}{(M_1+M_2+m_3)^2}, \tag{7}$$

where P_2 is the period of the third body, M_1 and M_2 are the masses of the primary and secondary components, m_3 is the mass of the third body, i is the inclination of the third body orbit, and a_{12} is the semi-major axis of the eclipsing binary system (Mayer 1990). And the sanity check for the Applegate mechanism is the subsurface magnetic field strengths required for the observed variation, which can be compared with literature values.

In addition to simply completing the analysis on these stars, further observational data may also be added to these records. Currently, the data set in this work does not include observations from big surveys like ASAS-SN and GAIA, this data will need to be added for a more complete observational record. Further, some photographic data is reported as start and end times of the eclipse, since the shape of the eclipse for all three stars is well defined this information can be used to find eclipse timings for these observations thus adding more data to the earliest observations.

Preliminary results indicate that the methods described in this work would be useful to apply to other RS CVn type stars, all of which have long observational lifetimes due to how bright they are, in order to further our understanding of how the periods of these systems change and whether or not there are any common trends.

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